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HYDRAULICS DIVISION

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INTRUSION OF SEA WATER IN TIDAL SECTIONS OF FRESH WATER STREAMS

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All fresh water streams which discharge through normal channels into a body of salt water such as the ocean, have salt or brackish water in their lower reaches more or less continuously depending upon the conditions at and near their mouths. This presence of salt water is of extreme importance to numerous economic activities. Though the existence of the estuary and the stream channel offers the opportunity for a port, the salt water itself is generally an unfavorable aspect. Few activities other than the fishing and some chemical industries can use highly saline ocean water and the latter which may require large volumes of ocean water from which to derive their products do not obtain that water from diluted estuaries. Most industries require fresh water, some in considerable quantity, and the economy thereof in a competitive society is of such moment that they select sites for their plants where the needed amount of fresh water may be had at low cost.

Large steam-electric plants are now located only where there is an abundant supply of fresh water for boilers and other features. Fresh water is necessary for domestic and commercial water supplies, and many port cities have been put to great expense to obtain water of the quality needed. The pursuit of agriculture in arid or seasonally arid regions requires fresh water for irrigation that crops may survive and flourish.

Salt water accelerates corrosion of harbor and marine structures, and of facilities in plants and factories. Marine borers flourish in saline waters. They attack and destroy, sometimes in short order, many structures, especially those made of wood, built in saline waters. Ships heavy laden with barnacles can be cleaned most facilely by spending a period in fresh water.

Those responsible for the maintenance of harbors and slips are extremely concerned over the presence of salt water in the harbor area for the contact between fresh and salt waters and the intermingling thereof is conceived as causing flocculation, agglomeration, and deposition of colloidal and other solids in fresh water. Large quantities of shoaling are attributed to this cause.

It is little wonder, then, that great interest has been shown in the subject of salt water intrusion into the mouths of fresh water streams. The subject was early recognized, and interest has intensified, for economic reasons, as the country has developed. Costly and extensive investigations have been made. In many cases specialized solutions have been developed and works constructed. Many of the problems have so far defied solution. The factors which control the intrusion are not widely or too clearly understood, and their inter-relations have not as yet been reduced to a status that will permit the engineer or scientist to predict what will happen as a result of the conjunction or the variation of the several factors. In short, the problem of salt water intrusion has not been reduced to an exact or near-exact science. Because of

the many factors involved the attempt to reduce it to such may be a futile one. But if analytical methods can be developed whereby an approximation of the answers desired can be arrived at with assurance, a great stride will have been made. Therefore, study of the problem continues by those with a purely scientific interest and those with both a scientific interest and a practical problem to solve.

Maximum Desirable Concentrations of Chlorine

Very few natural waters are completely free from salt. Minor amounts can be tolerated for practically all uses. There are limits beyond which use becomes unpleasant, undesirable or uneconomical. The limits vary with the use to be made of the water. Before a plant site can be selected, a source of irrigation water adopted, or a water supply system designed, the upper limit of salinity must be decided upon if the water proposed for use is saline or subject to becoming saline at times. In order to assist the reader in such a decision the following tabulation with references is presented:

TABLE I

Use	Max. Concentration Desirable parts/million of Chlorine
Irrigation	Extremely variable (1) (2)
Boiler Water	210 (1)
Domestic Use	(300 (1) (100 (3) (250 (4)
Industrial and Public Water Supplies	200 (5)
Prevention of Marine Borers	Variable with species (1)
Teredo Navalis	5000 (1) (Total salts)

For short periods considerably higher concentrations can be tolerated. For example in 1936 appreciably greater salinities than 250 p.p.m. chlorine occurred in the water supply at New Orleans. High salinities persisted for more than a month. The taste was unpleasant, but the water could be used for drinking purposes with, so far as is known, no harmful physiological effects.

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(1) "Report on Salt Water Barrier," by Walter R. Young, Bulletin No. 22, Division of Water Resources, Dept. of Public Works, State of California. This report makes reference to a "Report of the San Francisco Bay Marine Piling Committee," August, 1921, and 3rd Annual Progress Report.

(2) "Composition of Irrigation Water," by W. P. Kelley, Esq., and Discussion by Carl S. Scofield, Transactions A.S.C.E., 1941, Vol. 106.

(3) "Salinity, Mississippi River at and Below New Orleans, La.," Report by the New Orleans District, Corps of Engineers.

(4) U. S. Public Health Service, Public Health Reports, Vol. 61, No. 11, March 15, 1945.

(5) "Salinity Survey of the Delaware River," Sanitary Water Board, Pennsylvania Department of Health.

The amount of salt that can be tolerated in irrigation water depends upon the type of crop, the character of the soil, the nature of the underlying geological conditions, and the amount of crop retardation which will be accepted. Thus the limit of salinity for irrigation must be separately determined for each specific case.

The maximum saline content that will not cause flocculation of the solids in fresh water is of interest in connection with harbor maintenance studies. Although the exact amount is not known, in tests in connection with Charleston Harbor studies, it was noted that when 2% by volume of sea water was added to the fresh water which is discharged into the harbor, the settling rate of the particles was increased but the increase was not great. The concentration for this percentage of Charleston area sea water is estimated to be about 340 p.p.m. chlorine, or about 613 p.p.m. total salts. As indicated, this appears to be slightly above the limit of no flocculation if such a limit actually exists. Assuming that there is such a limit, it may be different at each locality so that similar tests should be made before a limit is selected elsewhere.

Relation Between Chlorine Content and Salts in Sea Water

Sea water contains many constituents (6). Regardless of the total salt concentration, the proportions of the major constituents remain approximately constant. The principle salt is sodium chloride (NaCl). As a result salinity has been expressed in parts per million of chlorine, of sodium chloride, and of total salts, as well as in specific gravity or density at a specified temperature. The following relations have been developed:

$$\text{Total Salts} = 1.29\ \text{NaCl(circa)}$$

$$\text{Total Salts} = 1.8050\ \text{chlorinity} + .030\ (1)(7)$$

Density - Salinity-Temperature Relationships

As indicated above, there is also a relationship between salinity, and density of sea water and various proportions of sea water. Figure 1 shows this relationship for a temperature of 15^{o} Centigrade with salinities expressed in parts per thousand of total sea salts. The densities of sea water and of mixtures of sea water and fresh water change with temperature, but the change is not great. Figure 2 shows the temperature - density relation for a salinity of 20 parts per thousand. It may be noted that the density at 35^{o}C (95^{o}F) is only about 1/2 of 1% less than the density at 15^{o}C (59^{o}F); also that the density at 4^{o}C (39.2^{o}F) is only about 0.1 of 1% greater than at 15^{o}C.

The changes in density with temperature at other salinity concentrations can be obtained from Figure 3 which shows the density - salinity relations for all temperatures from 0^{o} C to 35^{o} C. The salinity concentration below saturation will not change for a given sample of water with change in temperature. For example, if the water is heated it will expand, but since the weight does not change the proportion of salts in parts per thousand by weight does not change. Thus if one should desire to know the density of a sample of sea water at 10^{o} C which was measured at 35^{o} and found to have a total salt

(6) "Principles of Sedimentation," by W. H. Twenhoffel.

(7) "The Oceans," by Sverdrup, Johnson, and Fleming.

concentration of 30 parts per 1000, he may obtain this from Figure 3. As shown thereon, the density at 35^{o} C is 1.0168 and the density at 10^{o} C is 1.0230. The curves also show how the salt concentration must be changed with variation in temperature in order to maintain a constant density. Of course, the primary purpose of the curves is to permit determination of the salinity from the density for any temperature between 0^{o} and 35^{o} C.

Density of the Sea

At a temperature of 15^{o} C, pure fresh water has a density (specific gravity) of 0.9991, and the densest sea water has a density of 1.0310 and a salinity of 41.5 parts per thousand. The average salinity of the oceans is about 35 parts per 1000; thus the average density at 15^{o}C is about 1.026. The density of the sea varies along the coast line depending on the amount of fresh water flowing from the land and the nearness to the point of inflow of the fresh water. In investigating specific problems regarding salt water intrusion, the investigator will need to know the density of the ocean water with which he has to deal. Information of this nature can be obtained from publications of the U. S. Coast and Geodetic Survey. In order that the reader may have an appreciation of the densities along the Eastern and Southern coasts of the United States, and the variation thereof, Table 2 is presented:

TABLE 2 (8)

DENSITIES OF NEAR SURFACE SEA WATER
EASTERN AND SOUTHERN COASTS, UNITED STATES

Station	Period	Average Density (at 15^{o} C)	Salinity Parts/1000
Eastport, Maine	1930 - 1939	1.0234	31.6
Portland, Maine	1922 - 1939	1.0220	29.8
Boston, Mass.	1922 - 1939	1.0216	29.3
Battery, N. Y.	1927 - 1939	1.0157	21.6
Atlantic City, N. J.	1912 - 1939	1.0233	31.5
Charleston, S. C.	1922 - 1939	1.0222	30.0
Key West, Fla.	1926 - 1938	1.0269	36.2
Pensacola, Fla.	1924 - 1938	1.0124	17.3
Galveston, Texas	1922 - 1939	1.0175	23.9

The low densities at Pensacola and Galveston are doubtless caused by dilution from the Mississippi River and the numerous other sizeable streams which enter the Gulf of Mexico. The Hudson River has produced the same effect at Battery, N. Y.

(8) "Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena," Report No. 1, Committee on Tidal Hydraulics, Corps of Engineers, U. S. Army, February 1950.

Superposition of Fresh Water Over Salt Water

Assume that for a moment a globule of fresh water is at rest upon and in the surface of a body of salt water. The momentary condition is shown by the following sketch. (Figure 4)

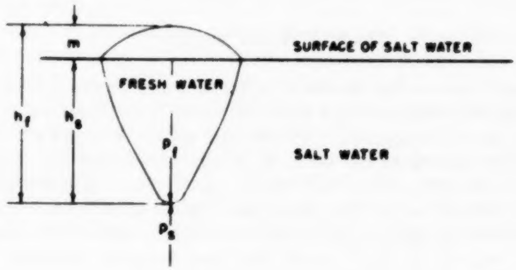

Fig. 4

Let --

h_f = Head of fresh water on bottom surface of the bubble.
h_s = Head of salt water on bottom surface of the bubble.
m = Height of fresh water above salt water surface.
p_f = Fresh water pressure.
p_s = Salt water pressure.
γ_s = Density (specific gr.) of salt water.
γ_f = Density (specific gr.) of fresh water.

In order that the bottom surface of the globule may not rise or fall, p_s must equal p_f, or

$$\gamma_s h_s = \gamma_f h_f$$

also

$$m = h_f - h_s$$

and

$$\gamma_s h_s = \gamma_f (h_s + m) = \gamma_f h_s + \gamma_f m$$

$$m = h_s \frac{(\gamma_s - \gamma_f)}{\gamma_f}$$

or

$$h_s = \frac{\gamma_f m}{\gamma_s - \gamma_f}$$

if

$$\gamma_f = 1, \quad h_s = \frac{m}{\gamma_s - 1}$$

Thus, to give this physical significance, if $m = 1$, and $\gamma_s = 1.025$, h_s will be 40. This means that with a salt water density of 1.025, there must be in feet of depth, 40 times as much fresh water below the surface of the salt water as there is fresh water, in feet of height, above that surface. Figure 5, was prepared to furnish a rather vivid portrayal of this situation.

It is evident that the fresh water, since it is superelevated above the surface of the salt water, will flow outward in all directions over that surface. As "m" reduces the bottom of the bubble rises rapidly. Flow will continue until the fresh water has been completely dispersed or has been thoroughly mixed with the salt water by turbulence and wave action. It is to be expected

then that whenever fresh water is discharged into and over salt water, fresh water surface currents will be set up as a result of the differential in densities.

Note that when the differential in densities changes either by rise or fall in temperature, or change in salinity of the salt or fresh water, the extent to which the fresh water bubble penetrates the salt water will be modified. Any material change will cause a substantial modification.

The Salt Water Wedge

That salt water enters the mouth of a fresh water stream and proceeds up the channel along the bottom when there is insufficient current velocity to prevent it has long been recognized. As the salt water is found at or near the surface beyond the mouth of the stream, it was conceived that the plane of the upper surface of the salt water must slope upward in a downstream direction. The body of salt water below this plane was referred to as the salt water wedge. Measurements have confirmed to a certain extent this conception. At some points relatively fresh water has been found at and near the surface with salt water occurring in the lower layers. However, this does not appear to be the usual case. Generally there is no fine line of demarkation between the fresh and the salt water, so that there is no distinct wedge. Though the salinity increases with depth, it is usually found that when salt water appears in the bottom of a channel, a measure of salinity will be present at the surface and at all depths. This is shown clearly by Figures 11 to 14 inclusive. In the case of the Calcasieu River (Fig. 13) the salinity at the bottom did increase about one hour before an increase was perceptible at the surface and mid-depth. It is believed that this may be expected at sections in close proximity to the source of salt water when the fresh water discharge is high, for the reversal from ebb tide to flood tide occurs slightly earlier near the bottom than at higher levels, and this differential in time is greater for high fresh water discharge than for low discharges. Thus if the salt water has been swept out by the ebb flow, there will be sufficient time during the tide reversal for salt water to flow upstream on the bottom past a station near the mouth of the river while fresh water is still flowing downstream in the upper levels.

Figure 6 shows vertical-salinity curves observed at Station 29, Charleston, S. C., Harbor. This station was located in the ship channel near Fort Sumter only a few thousand feet from the jetties which extend into the Atlantic Ocean. The curves reveal that salt is to be found at all levels regardless of the stage of the tide. They also confirm the statement that salinity increases with depth. This indefinite character of the so-called salt water wedge is no doubt caused by the fact that salt water does move up stream principally near the bottom and in the lower levels of the stream, and that by diffusion, erosion of the surface of the wedge by the current, and turbulence it is mixed with the fresh water near and at the surface. This saline water is then carried downstream over the more salty layers below with the mixing process continuing so that there can be no sharp juncture between fresh and salt water, except under special conditions recognized above.

A reasonable definition for the location of the surface of the salt water wedge might be the level below which there is little or no change or increase in salinity. An attempt has been made to draw a line through points on such a surface on Figure 6. It may be observed that the points could not always be selected with accuracy. Moreover, observation of other vertical salinity

curves has shown that the face of the salt water wedge so identified is frequently not possible to locate. At upstream stations, for example, past which the wedge transits with the ebb and flow of the tide or near such a location, thoroughly mixed brackish water may move upstream with the flood tide and past the station once more with the ebb tide. The salinity of the water would be rather uniform with depth. In such a case, the wedge under the above definition might be interpreted to be at the surface, whereas, perhaps the true wedge did not reach the station. Nevertheless, the definition may be of value.

In most problems, the location of the so-called wedge is of little importance. The important factor is the degree of salinity. Therefore, it is more practicable to view the surface of the wedge as delineated by an isochlor, a line of equal salinity, or a line of equal density or specific gravity. These lines are more readily determinable than any theoretical interface. Figure 7, although obtained from a model of Savannah Harbor, Georgia, is a good example of equal density lines. It also shows the change in shape, slope, and location of these lines from low water slack to high water slack of the tidal cycle.

Theoretical Wedge Shapes

When bodies of fresh and salt water standing at the same level are separated by a diaphram and the diaphram is suddenly removed, an instant thereafter, the profile of the interface will be as shown in Figure 8. (9) (10)

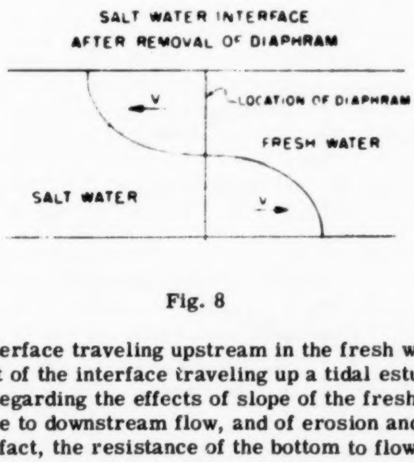

Fig. 8

The shape of the interface traveling upstream in the fresh water should be quite similar to that of the interface traveling up a tidal estuary during the rise of the tide disregarding the effects of slope of the fresh water surface caused by resistance to downstream flow, and of erosion and other factors causing mixing. In fact, the resistance of the bottom to flow of the salt water could well accentuate the curvature of the interface adjacent to it so that the interface could slope backward in a downstream direction just above the bottom. The phenomenon is similar to the progression of a mass of cold air into a warm air mass causing a cold front. This drag on the bottom producing a tendency of the salt water to slightly over-run fresh water layers immediately above the bed would cause mixing in that zone because of the differential in densities, resulting in downward movement of the salt water

(9) "Model Law for Motion of Salt Water Through Fresh," by Morrough P. O'Brien and John Cherno; Trans. ASCE, Vol. 99, 1934.

(10) G. H. Keulegan in "Hydraulic Engineering," edited by Hunter Rouse.

displacing fresh water and mixing with it. This may, at least in part, account for the fact that the near bottom salinities generally increase during the early stages of the flood tide as shown on Figures 6, and 14, even though the salt water wedge does not appear to have been swept downstream below the station on the ebb tide, and that those salinities decrease with progression upstream of what appears to be the wedge. (Station 18, Charleston Harbor, is about 10 miles upstream from Station 29). The tendency, of course, would be to further mask the wedge beyond the masking produced by other mixing processes.

On the basis of the assumptions that there is a true interface between the fresh and the salt water in a flowing fresh water stream, that the salt water wedge has become stabilized with no flow therein, and that the body of salt water into which the stream discharges maintains a constant level, an approximate delineation of the salt water wedge has been made which, though no claim is made for exactitude, will enable interesting conclusions to be drawn as to the nature of the wedge and its movements as the result of channel modifications, surface elevation changes, and increase or reduction in discharge.

A flowing stream slopes in the direction of flow. As indicated by the derivation made in connection with the foregoing discussion of the salt water bubble, in order that a higher elevation of the fresh water may be maintained at an upstream point than at a downstream point, the surface of the salt water must slope in the opposite direction to the slope of the fresh water surface. Figure 9 shows this condition for two points a distance dx apart along the channel.

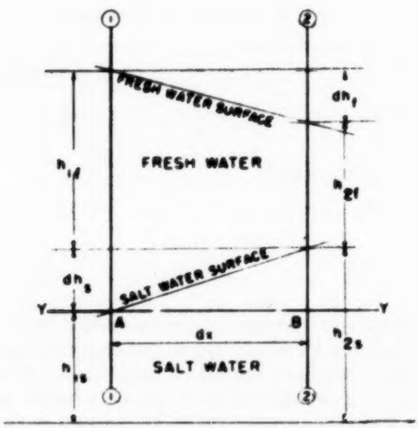

Fig. 9

Neglecting the effect of velocity impinging upon and deflected by the salt water interface, which will be shown to be small for moderate velocities and slopes of the interface, for no flow to occur in the salt water wedge the pressure at all points on the plane Y - Y must be equal to the pressure at B.

Then ---

$$dh_f\gamma_f + h_{2f}\ \gamma_f + dh_s\gamma_f = h_{2f}\,\gamma_f + dh_s\,\gamma_s$$

$$dh_f\ \gamma_f + dh_s\gamma_f = dh_s\ \gamma_s$$

$$dh_s\ (\gamma_s - \gamma_f) = dh_f\gamma_f$$

$$dh_s = dh_f \frac{\gamma_f}{(\gamma_s - \gamma_f)}$$

The subscripts "f" and "s", respectively denote fresh water and salt water, and γ (gamma) represents the density. It may be noted that this is identical to the equation developed for the depth of the salt water below the fresh water bubble except for the substitution of differential heads.

Using the above relation and neglecting the change of velocity head from section to section backwater curves of the fresh and salt water surfaces were computed as shown on Figure 10 for fresh water flows of 10 and 30 cfs per foot width of channel. A depth of 5 feet of fresh water over the salt water was assumed at the point of beginning of the backwater curves. The computed surfaces are shown by the solid lines on Figure 10.

The computations indicated that for the magnitudes assumed, the inclusion of the change in velocity head from station to station would have very little effect on the surfaces. To determine whether the deflection of the fresh water velocity by the salt water surface would materially modify the shape and position of the surfaces, an analysis was made on the assumption that the fresh water velocity was directed parallel to the axis of the channel and that it was deflected by the salt water surface into parallelism with that surface. For the discharge of 30 cfs per foot of width, which is more critical than the discharge of 10 cfs per foot, it was found that the depression of the salt water surface because of this deflection, for the reach between channel distances of 10,000 ft. and 20,000 ft., would be only about 0.07 foot, and for the reach between channel distances 0 and 100 feet would be less than 0.6 foot. From the foregoing it was concluded that the neglected factors would not affect deductions which might be made from Figure 10.

The water surface profiles drawn on Figure 10 show that the salt water wedge is concave upward when it is defined by an interface and when fresh water flows and the water surface elevation of the salt water source have remained constant for the time needed for stabilization of the wedge. The wedge retreats substantial distances when flows are increased, and the more nearly horizontal is the bottom the greater is the retreat. In fact, a bottom with an adverse slope will facilitate a greater retreat than one with a positive slope in the direction of fresh water flow unless the bottom remains below the surface of the wedge for the higher flows. It should be noted however, that when the tide rises and falls and if there is no reversal of direction of fresh water flow, the wedge will neither advance or retreat as far as indicated by the stable conditions assumed in the calculations. There is insufficient time to establish or approach stability on either the rise or fall of the tide so that the wedge cannot reach the limits that would be attained with constant flow and head. It has been noted, for example, that in long periods of low flow the salt water penetrates further upstream than in shorter periods of low flow. Moreover, field observation has revealed that a moderate high tide with a high low tide will force salt water further upstream than a high high tide preceded and followed by a low low tide. A series of high low tides succeeded by a high high tide will evidently produce the greatest advance of salt water.

When the tide reverses the flow in the stream, the slope of the fresh water surface is adverse tending to permit the salt water to rise to as high an elevation upstream as below. This encourages a greater upstream flow of salt water. As a result, when the tide falls and the slope reverses once more there is a greater volume of salt water to be evacuated from the channel than would be the case had the adverse slope not occurred. Perhaps in the lack of balance of the fresh water head and the continuous change thereof with the ever changing tide, and in the volumetric characteristics of the channel lies the explanation that at many stations where the flow reverses (See Figures 11 through 14) and the bottom velocities approach or even exceed the mid-depth and surface velocities during certain phases of the flood tide and the initial and final stages of the ebb.

If the level of the salt water source is increased, the entire plans of the curves shown on Figure 10 is raised. The shape of the curves is not changed so that the wedge merely extends further upstream along a curve parallel to the one applicable to the lower salt water source. The change is similar to that which occurs when the bottom is lowered parallel to the original bottom which permits the wedge to move upstream along an extension of its original surface until the new bottom is intersected.

One factor which is of proportionately more importance in shallow streams than in deep ones should be noted. As the tide rises, not only is the downstream flow decreased and possibly reversed, but a greater area and depth is provided for upstream flow of salt water. The salt water velocity is increased, which may permit the salt water to approach the limit of encroachment of the wedge under non-tidal conditions with a lower constant stage of the salt water source than the height of the tide. Thus it might be possible by use of a model to establish equivalent non-tidal stages and flows which would enable further analyses to be made without use of the model. For the same flow conditions but change in tidal height, the increased depth of the salt water prism would cause the limit of encroachment of a high tide to appear out of proportion to the limit of a lower tide.

The dashed lines on Figure 10 were computed on the basis that water above the wedge is increased in quantity and density by mixing with water eroded from the wedge. The assumptions are shown on the drawing. No modification was made for upstream flow in the wedge. Instead the depth was considered to be substantial so that this would have little effect. It is interesting to note that on the basis of the assumption that the density of the "fresh water" prism at station 0 was 1.020, indicated by Figure 7 as not too variant from experience, almost 2/3 of the water flowing downstream in the lower 3000 feet of channel was salt water eroded from the wedge. The diffusion of salt water through the fresh water prism materially altered the shape of the wedge. This, of course, is caused, only in part by increase in downstream flow over the wedge which can be seen from the fact that the fresh water surface for this condition is lower than the fresh water surface under the assumption of no erosion from the wedge. Of probably greater effect is the increase density of the "fresh water" prism. The equation on page 9 shows that as the density of the two liquids approach equality, the height of the column of the lighter liquid supported by the heavier increases rapidly for a fixed amount of superelevation of the lighter liquid. Figure 6 and other data from field and model observations show that the assumption of a "fresh water" portion that is partially salt is in accord with actual conditions.

Current-Salinity Observations

Figures 11, 12, 13, and 14 present tide, current, and salinity data for four streams in the southern United States, three of which are on the Atlantic seaboard, and one on the Gulf of Mexico coast. The data for all these streams manifest common characteristics. The salinity is greatest near the bottom and reduces in the vertical toward the surface. High water slack, here termed as the point of zero velocity, occurs slightly beyond the flood tide crest. Salinity is generally greatest at about high water slack. The bottom currents change from ebb to flood a short time before the change occurs in the top currents. The currents at all levels during the last part of the ebb, the first stages of the flood, and at times during the last stages of the flood and the first portion of the ebb are of nearly the same magnitudes. The explanation that this may be in part due to unbalanced density heads caused by changing slopes has been given previously. On Figure 12 it may be seen that the currents at all levels were approximately the same for about 5 hours from near low tide to just beyond the point of inflection on the rising tide curve. This was the case for about 4 hours in Savannah Harbor (Figure 11) and 3 hours in the Calcasieu River (Figure 13). In fact, in Savannah Harbor, Station 143, the velocities at mid-depth and bottom were greater than the surface velocity for practically the entire flood period. In the instance of Charleston Harbor (Figure 14), the complete increasing portion of the current curves is not available, but there is a period of about 4 hours on the flood curves when the differences in velocities from top to bottom are not great. It may be noticed also that there are briefer periods near high water slack when current differentials are small.

The Calcasieu River, Figure 13, with only a slight indication of a double tide in 24 hours, and for which the data were taken during a relatively high discharge for that stream, illustrates interesting variations. The salinity is very low during low tide, in fact, the river is almost fresh because of the high river discharge. When the tide rises the salinity increases precipitously near the bottom and thereby gives evidence of the existence of a distinct wedge for a short time. The salt water is slower in reaching the higher elevations. The salinity in the upper layers continues to rise until high water slack which occurs at about low stage of the higher low water phase of the tide. This long delay was doubtless caused by the large storage area in Calcasieu Lake above the station. It was necessary for the river flow to fill this storage before it could overcome the rise of the tide from lower low water to higher low water. Once the storage area was filled sufficiently to force outward flow past the station of observation the slight rise to lower high tide which followed was not sufficient to counterbalance the slope in the connecting channel from the lake to the Gulf of Mexico in which the station was located. Therefore, the currents continued to ebb. It appears that because of the return of salt water which had previously been forced upstream and possibly into the lake, the salinity remained relatively constant except near the surface until beyond the crest of lower high tide.

The area of the flood portion of a current curve is a measure of the distance upstream which the water at that level would travel if the velocities at that level were the same at upstream points. Thus for the Calcasieu River the water near the bottom should have traveled upstream during the flood tide about 33,000 feet. The salt water which appeared at the station at near hour 4 should have traveled upstream about 26,000 feet. It may be noticed that the last of the salt water returned past the station at about hour 16. The area

under the ebb current curve to this hour indicates, on the basis of the assumption made above that the currents upstream were the same as at the station, that the upper limit of the salt water on the bottom traveled about 14,000 feet to reach the station. The distance of the lower limit of Calcasieu Lake is only slightly less than this. Evidently the velocities were not the same at upstream points as at the station of observation, and the dampening effect of the lake on velocities, limited the upstream travel of the salt water.

Except where modified by special conditions which alter the velocities or by nearness of the salt water source, the salt water would be expected eventually to travel upstream above a station a sufficient distance so that the entire wedge would not return past the station on the ebb tide when the area under the bottom flood current curve is greater than the area under the bottom ebb current curve. The converse would be expected to be true, that is the salt water wedge would eventually be held below the station, when the area under the bottom ebb current curve exceeds the area under the bottom flood current curve. However, should the source of salt water be near the station and the ebb current push the salt water completely out of the estuary, the wedge can still reach the station if the distance of travel as shown by the area under the bottom flood current curve is greater than the channel length from the mouth of the river to the station. In the case of the Calcasieu River, a good example of this, the area under the bottom flood current curve was equivalent to a travel distance of about 33,000 feet, a distance considerably greater than the length of the channel between the station of observation and the Gulf of Mexico. Thus for the conditions under which the data were observed, the salt water can be expected to continue to reach the station even though the area under the bottom ebb current curve exceeds greatly the area under the bottom flood current curve.

Except for sporadic variations, wherever there is continuous downstream fresh water flow, the area under the top ebb current curve must be greater than the area under the top flood current curve.

The foregoing examples and expositions emphasize the necessity of analysing each stream and station separately considering the peculiar conditions which apply to each. General explanations and rules for all locations and conditions cannot be propounded, and conclusions based on generalities are fraught with chance of error. Data must be obtained and analyzed for each individual location and problem. But a general knowledge of phenomena and interpretations elsewhere will facilitate the analysis and aid in arriving at correct solutions.

Effect of Intruding Salt Water on Vertical Velocity Curves

Inspection of the current curves on Figures 11 to 14 inclusive will show that the relations between top, mid-depth, and bottom velocities change with the tidal cycle. As indicated previously, the bottom velocity is not always low in comparison with the top and mid-depth velocities as is the case for fresh water channel flow unaffected by tide and salinity. It is believed, as explained above, that this is at least in part caused by additional head near the bottom imposed by differences in density of fresh and salt water coupled with unbalance in fresh and salt water heads resulting from changing slopes as the tide rises and falls through the tidal cycle at continusously changing rates.

Figure 15 shows vertical velocity curves at one point in Charleston Harbor through a major portion of a tidal cycle. It may be noted that during the flood portion of the tidal cycle, the vertical velocity curves do not exhibit normal vertical velocity conditions, but that from shortly after ebb begins to about low tide, the curves approximate normal curves.

This changing nature of vertical velocity curves in tidal reaches, especially where salt water is present has made the measurement of discharges in those reaches a difficult procedure. In order that discharges may be obtained accurately on all stages of the tide it is necessary that observations be made almost simultaneously across the measuring range and at several points in each vertical. Because of the seeming approach to normal vertical velocity curves of many of the ebb tide curves an examination of curves at one range in Savannah Harbor has been made. A comparison between the average of 12 of these curves and a normal vertical velocity curve is shown on Figure 16. The two curves cross at 0.6 depth at about 100.5% of the mean velocity. This is the depth at which velocity is measured in many regular discharge observations. Measurements are also frequently made by observing velocities at 0.2 and 0.8 depth and averaging the two. The average of these points on the ebb tide curve is 99.5% of mean velocity and the average on the normal non-tidal curve is 100.5% of mean. When the two extreme ebb tide vertical velocity curves are omitted, the average of the remaining curves exhibits a velocity of 101.6% of the mean velocity at the 0.6 depth point and of 100.0% of the mean velocity for the average of the 0.2 and 0.8 depth points. A little computation will show that measurement at the 0.6 depth point or at the 0.2 and 0.8 depth points on the ebb curves presented on Figure 15 for Charleston Harbor would also give fairly accurate determinations of the discharge during the ebb periods.

The foregoing observations may present a means of saving time and labor for the engineer attempting to measure discharge in tidal waters. They indicate that when the flow is ebbing, it may be satisfactory to determine discharge by measuring velocity only at the 0.6 depth point or at the 0.2 and 0.8 depth points. On other phases of the tide it may be necessary to make complete traverses, although if it is found that vertical velocity curves show almost a constant velocity from top to bottom as is the case on Figure 15 for a goodly portion of the flood tide phase, measurement of velocity at not over three points in the vertical should suffice. Before the work can be abbreviated in this fashion at any station, complete observations should be made and analyzed so that the methods adopted in order to expedite and minimize the work may furnish results of the required accuracy. Each station may be a problem unto itself and the accuracy required will depend upon the purpose of the measurements.

Flocculation and Deposition

Much of the recent study of salt water intrusion into fresh water streams has been prompted by flocculation of clayey materials in colloidal solution and the accelerated deposition of the flocculated material and material in suspension which may become aggregated therewith. Evidence points to a large amount of troublesome shoaling in navigation channels from that source. Fresh water streams carry colloids toward the ocean. When their waters become intermingled with salt water, the colloids are flocculated. They aggregate and assume weight and dimensions sufficient to permit deposition under favorable conditions. There is little doubt that the flocs combine with heavier

substances in suspension to increase the weight and density of the flocs similar to the action which takes place in a water treatment settling basin. The same processes occur when colloid bearing waters mix with waters containing other electrolytes than sea salt or colloids of opposite electrical sign. The process of coagulation of colloids has been described by Twenhofel (6) in considerable detail, and by Mr. G. H. Matthes (11).

In experiments to determine approximate settling rates of coagulated material with varying quantities of sea water, Mr. E. A. Schultz, Engineer, Charleston District, Corps of Engineers, used sea water and fresh water containing colloids from the vicinity of Charleston Harbor. He found that when 2% by volume of sea water was mixed with the fresh water, there was a small increase in settling rate. When the sea water was increased to 10% by volume the increase was material. The rate of settlement further increased moderately when the volume of the sea water was 50% of the mixture. Sverdrup, Johnson, and Fleming (7) state:

> "Little is known concerning the state of aggregation of the clay and colloid particles that are in suspension in the sea; however, studies by Gripenberg (1934) have shown that fine grained material when mixed with sea water tends to flocculate into units which settle with velocity equivalent to those of quartz spheres between about 5 and 15 microns in diameter, that is, they settle between 1m and 20m per day."

The shoals formed from the flocculated material vary in density in accordance with depth below the surface of the shoal. The density is increased by the squeezing out of water by the superimposed load. When first deposited the material is very little heavier than water. Sampling of shoals in Charleston Harbor revealed that a cubic foot of shoal may weigh from about 70 to 90 pounds and that the solids may weigh from only a pound or two to as much as 50 pounds or more. The density increased rapidly to a depth of 6 feet in the shoal. Below that point to a depth below the surface of the shoal of about 25 feet, the density remained rather constant at 20 pounds of dry material per cubic foot of shoal.

It appears apparent from the foregoing densities that flocculated colloids and very fine particles retain with them when deposited in shoals very large amounts of water. Therefore, small amounts of colloids and clay in the fresh water stream can cause shoals many times their volume. In investigating sources of shoaling when flocculation is present, this fact must be kept in mind.

One problem concerning flucculated material that has been troublesome to solve is the mechanics whereby such light material is settled and deposited in a stream where the flow is turbulent at all times except near high water and low water slack. Flocculated material is very light although it has been indicated above that it may agglomerate into particles which have a settling velocity of 1 to 20 meters a day. However, were the flocs of the nature of those formed in a water supply settling basin, it would be difficult to imagine them settling under the condition of turbulent flow present in many of the harbors that experience shoaling by this material. It would be even

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(11) Paper presented at the Federal Inter-Agency Sedimentation Conference, Denver, Colorado, May 6-8, 1947, by Gerard H. Matthes, Consulting Engineer.

less possible to imagine the material staying on the bottom in the form of a shoal in the presence of even mild velocities. These realizations have probably led to the assumption, generally made in the past, that the material was to a great extent precipitated and arranged in shoals during slack tide. In explaining the shoals, and searching for most likely places for shoals to form, long periods of slack near the channel bottom were sought. While such periods are without doubt favorable for the formation of shoals, it is believed that they are not the sole parameter contributing to such formation. The data shown on Figures 11 and 14 were obtained in the vicinity of shoal reaches; yet both of these exhibit only brief periods of slack tide.

Considerable space was given above to discussion of periods in the tidal cycle when velocities were almost the same at all levels in the stream. A partial explanation for this phenomenon was ventured. The current curves on Figure 12 offer a good example. For over 4 hours there was no material difference in velocity from top to bottom of the stream. Since vertical turbulence transfer is proportional to the rate of change of velocity in the vertical, there should be little tendency during this period for turbulence to prevent settlement of suspended matter. In fact, for a period of about two hours from hour 4 to hour 6 what tendency there is for turbulence to transfer sediment should be in the downward direction since the velocity at the bottom is slightly in excess of velocity at other levels. During these hours, also, low water slack occurred. Thus an extended period is provided for suspended sediment to settle toward the bottom. As it becomes more concentrated, the weight increases, and as a result of the superimposed load doubtless some becomes sufficiently dense to cling to the bottom at most favorable locations. The slack periods without doubt encourage shoaling for they provide times when concentration can take place without lateral movement. Though some of this material may be dispersed once more during other phases of the tidal cycle when the upper currents exceed those at the bottom, doubtless some or much of the sediment which has been concentrated at the lower levels remains there to receive further additions from succeeding periods of practically uniform velocity from top to bottom. The shoals are then most likely to form at locations of low velocity, just as is the case with coarser material, where the concentrated material can best come to rest and resist the velocity.

The situation as described permits the flocculated sediment in the less saline water to pass into the more saline water, or into the wedge. When the areas of the near bottom flood and ebb current curves are very nearly the same, the material entrained in the bottom currents will merely shift back and forth along the channel and will not be discharged from the river unless the mouth is sufficiently near to permit the water ebbing past the station to reach the mouth. Ample opportunity is then provided for increase in concentration, gradual consolidation, and for the finding of a suitable place of deposition. This is true also when the areas under the flood and ebb curves are not the same, but are not greatly divergent, for the net transport will be small. The material near the bottom will gradually be transported either upstream or downstream depending on whether the ebb or the flood currents near the bottom are preponderant. With the area under the ebb current curve the greater, the material will have a net movement toward the river mouth. In its travel downstream it may encounter a location where the ebb and the flood are in balance. This then would appear to be an ideal area for deposition because after movement in either direction the sediment would be returned to this point. Such a location is likely to exist whenever the ebb current is not of sufficient magnitude to drive the salt water out of the stream,

for as the mouth of the river is approached more and more water is eroded from the salt water wedge which is replaced by inflow from the sea along the bottom. Thus the shift from a preponderant ebb flow along the bottom to a preponderant flood flow is to be expected.

Likewise, if the bottom flood flow is preponderant, the sediment near the bottom will gradually work upstream until the fresh water flow of the stream changes the bottom currents so that the ebb becomes the greater. Generally it would appear that this should occur about halfway between the limit of intrusion of the so-called salt water wedge and the limit of retreat. The upstream limit of the wedge will probably be downstream from the first appearance of saline water, because the latter will be carried beyond the wedge by the waters in the upper levels of the stream. This location where flood and ebb near the bottom are equal should also be one favorable to the deposition of flocculated sediment as was the case previously descrived. The two cases are identical in every respect.

Problem Solutions

Methods for solving the problems created by the intrusion of salt water into fresh water streams can be divided into two principle categories: (1) Preventive, and (2) Remedial. Each can be broken down into additional classifications. Complete prevention or remedy is not always possible or economic although partial measures may be practicable. If, for example, 5 or 10% of the shoaling can be prevented or induced to occur where removal is less costly than in its original position, enormous sums expended on dredging may be saved. Therefore, methods which offer promise of partial prevention or correction are included in the following discussion.

Prevention of Salt Water Intrusion

Salt water intrusion can be prevented by the construction of dams to interrupt the upstream movement of salt water. Weirs and contractions may also offer means of preventing or reducing upstream movement. If it is desired to keep salt water from passing the weir or contraction, the design must be such that the fresh water velocity and head created by the works will be sufficient to counterbalance differential density head, at all levels between the contraction devices or at the level of the weir crest during the highest tides in conjunction with the lowest fresh water flows. Should it be practicable to suffer occasional passage of salt water, the cost of the works can be reduced. In designing contraction works, the lower velocities on the bottom than at higher levels must be considered. Unless these velocities are increased to prevent it, salt water will pass the works along the bottom. Under any condition weirs and contractions reduce the volume of salt water which can flow upstream during the flood tide and, therefore, should lessen the extent of the penetration.

When a barrier is placed across a stream, a lock must often be installed. Salt water will pass upstream through the lock during lockages unless provisions are made to prevent it. With an abundance of fresh water flow, this may not be serious, for the salt water will be kept in the vicinity of the barrier through erosion of the salt water prism by fresh water flow and discharge of the mixed waters over the spillway or through sluices. However, if the barrier has materially increased the elevation and cross section of the fresh water stream so that velocities are greatly lowered, the salt water may move considerably distances upstream, possibly farther than prior to construction of the barrier. This problem has been solved in the past by providing a salt

water sump upstream from the lock with facilities for flushing the salt water in the sump through the dam or barrier. Several years ago, the U. S. Waterways Experiment Station conducted a series of tests and devised a system for flushing a lock during lockage operations which was successful in preventing salt water from passing the lock. An excess of fresh water over that needed for lockage is required.

Salt water intrusion may be prevented by increase in fresh water flow or by a combination of channel constriction and increase in fresh water flow. Increase in flow may be accomplished by construction of storage reservoirs or by diversion. Besides increasing low water flow, reservoirs serve beneficially as desilting devices. In case of diversions, unless the flow is increased sufficiently to force the salt water from the mouth of the stream, shoaling may be aggravated when the diverted water contains suspended matter or colloids. Moreover, diversion raises the average flow of the stream, and since the channel size and configuration is fixed in general by the average flow, diversion may intensify shoaling conditions for an extended period until the channel becomes adjusted to the new average flow. Even though the increased flow cannot prevent salt water instrusion for all conditions of the tide, should it be able to flush the salt water out occasionally, shoaling should be reduced in a channel where coagulated colloids are found, for this will interrupt the upstream and downstream shift of the flocculated material entrained in the bottom currents by evacuating them from the mouth of the stream.

Reduction of Silting

The amount of suspended material and possibly colloids contained in the fresh water stream can be reduced by watershed treatment. This is being practiced quite widely in the United States for the prevention or suspension of erosion, but without regard to shoaling in harbor areas. For this work to be most effective for harbors and estuaries, the watersheds that contribute the most to shoaling must be identified and the treatment carried to completion there as rapidly as possible.

The construction of storage reservoirs may be considered as an item in watershed treatment. Large reservoirs will serve as settling basins and permit the deposition of finely divided material thereby withholding it from harbor areas. The effect of a reservoir on colloids, if any, is not known. It is probable that it has little effect unless the reservoir provides access to colloidal organic matter which serves as a protective colloid to prevent flocculation. With an adequate amount of protective colloid present in the water entering a harbor, flocculation may be prevented or reduced permitting the colloidal material to be carried out to sea with the fresh or comparatively fresh water.

A settling basin is effective when most of the shoaling material is noncolloidal. Unless an existing basin can be accommodated to this use by diverting the stream through it, the provision of a settling basin would be costly. At times, side channel settling basins can be obtained by excavating cutoffs. The old bendway channels will then serve as settling basins to remove portions of the silt from the water that passes through them.

If the source of shoaling material is bank caving, the receding banks may be stabilized by revetment or other means. This may not be effective at once, for the prevention of bank caving may induce deepening of the channel if there is a substantial amount of bed load derived from the banks. The deepening will continue until velocities are reduced below the capacity to erode the bed.

Siltation may be prevented by diversion of the fresh water stream so it does not enter the harbor. This transforms the harbor into a salt water arm

of the sea. Before this is attempted an appraisal should be made of the possibility that sand from the ocean bottom may be carried into the harbor area by the flood tide and not returned by the ebb. Partial diversion of the fresh water flow may reduce silting. It may also alter the location of shoals. If their locations can be changed to minimize dredging or to make the dredging operation less costly, the diversion may be worthwhile.

The addition to the fresh or harbor water of a protective colloid or a counter electrolyte would prevent flocculation and deposition. However, at the present time, it appears that addition of an adequate amount of this counteracting material would be prohibitively costly.

Prevention or Reduction of Channel Shoaling

It has often been suggested that channel shoaling can be prevented from increasing or reduced by maintaining the tidal prism or enlarging it. Unless the near bottom currents are increased sufficiently to force the deeper layers of water beyond the mouth of the river occasionally so that the silt and coagulated material entrained in those layers is evacuated to the ocean, this method may not be effective. It should, however, change the location of the shoals.

Under special conditions the increasing of the tidal prism may be the incorrect maneuver. It increases the flood currents as well as the ebb currents. If the bottom flood currents are increased, the point of equality of the areas of the bottom flood and ebb current curves (see Fig. 11) is moved upstream. This may perpetuate the existing shoaling condition, expecially in branch channels downstream from that point of equality. The opposite action, that of reducing the tidal prism above and immediately below a branch channel where shoaling is occurring, may result in moving the point of equality downstream from the branch channel thereby creating in the lower layers a preponderance of ebb tide flow over flood flow. This should shift the point of shoaling in the main channel downstream, and may reduce shoaling in the branch channel. The existence of a substantial fresh water discharge makes this end easier of accomplishment.

The concentration of currents to prevent deposition or to relocate shoals may be successful if the lower layers of the water are frequently discharged from the mouth of the river and the relocated shoals will not be troublesome or can be dredged at less cost. Dikes and groins can produce this effect locally. They may be able to concentrate the currents sufficiently to create a preponderance of bottom ebb flow at their locations. This should reduce upstream shoaling. Dikes and groins constrict the upper levels of a channel cross section. Therefore, they should be especially helpful in increasing lower level flows.

Though the closure of branch and chute channels, and sloughs will reduce the tidal prism, it will concentrate the remaining tidal flow and all of the fresh water in the main channel. Generally this should increase currents in the main channel. However, since many of the side channels may be shallower than the main channel and the bottom outflowing currents in them are probably lower than higher level currents, their closure may not increase the bottom currents in the main channel materially. From this standpoint closure of side channels appears to be inferior to the provision of groins and dikes. However, the latter are local in effect so far as currents are concerned, whereas the closure of side channels may increase average velocities through long stretches of a harbor.

Tidal basins have been used to increase ebb currents through portions of harbor channels. By the construction of the necessary structures and the provision of automatic gates, water was taken into the tidal basin at

Washington, D. C., from the Potomac River on the rise of the tide and discharged through the harbor channel on ebb tide. Similar arrangements have been investigated for Savannah Harbor by model experiment. (12) The size of the basin and the amount of water which can be admitted to and discharged from it in relation to the channel through which it is discharged have a great effect on the efficacy of the basin.

Should the theory of shoaling by flocculated material that has been expounded above, including the upstream and downstream movement of this material which has settled and concentrated in the lower layers of the stream, be substantiated, there may exist at some locations the opportunity to divert this entrained sediment. If a nearby basin exists which can be connected to the harbor channel and to a separate outlet to the sea, a diversion may be excavated to this basin from a proper location along the main channel and at an optimum angle therewith for the purpose of diversion of sediment. (13) A structure gated near the bottom that will permit water and silt to flow into the basin from the harbor channel during the flood tide should be constructed. A similar structure that will allow flow from the basin to the sea during the ebb tide through the separate channel should also be constructed. This type of basin is similar to the tidal basins described above, but it is operated exactly in reverse. Water is taken out of the harbor channel near the bottom on the flood tide, and discharged from the basin to the ocean or to an alternate channel connected with the ocean on the ebb tide. That these works will eliminate shoaling is not to be expected, but if they are successful in diverting sediment, they will reduce shoaling. It may eventually be necessary to dredge from the basin, but if the basin is located where spoil areas are close at hand, the dredging should be less costly than harbor dredging where spoil areas may not be conveniently located, and because of the concentrated area in the basin to be dredged.

Reduction of shoaling in the channel can oft-times be accomplished by relocation of the channel. Study of the harbor area will show where shoaling may be expected to be less than in its original location. But before a decision is made, the harbor currents should be studied also. Usually the principal flood and ebb currents do not follow the same axis. The avenues of the near bottom flood and ebb currents should especially be noted. Should the bottom ebb currents be preponderant over the flood currents in one location and of sufficient magnitude and duration to carry material through the relocated channel, it is probably that that location should be adopted for the relocation. If they are not capable of carrying the bottom layers through the relocated channel, it is possible that the channel should be sited where the flood currents are the greatest. Detailed study of each proposed relocation and each area where relocation might be beneficial is required. A model can be of great assistance in such studies. It can predict with reasonable accuracy what change will take place in the currents as a result of relocated channels or other works.

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(12) "Plans for Improvement of Navigation Conditions and Elimination of Shoaling in Savannah Harbor, Georgia, and Connecting Waterways," Technical Memorandum No. 2-268, U. S. Waterways Experiment Station, Vicksburg, Mississippi.

(13) "Diversions from Alluvial Streams," by C. P. Lindner, Proceedings, A.S.C.E., Volume 78, Separate No. 112.

Removal of Shoals and Shoaling Sediment

Pipe line cutterhead dredges have usually been employed for removal of shoals in protected harbor areas. When the shoals are removed, the light slurry near the bottom in the shoal area is also pumped through the dredge. The procedure is simple, but the operation is often complicated and made costly by the lack of availability of suitable and convenient spoil areas. On the outer bars and sometimes well within the harbor area where the pipe line required to reach a spoil area is too long for economic operation of a pipe line dredge, the hopper dredge is used.

Agitation dredging has been employed many times with apparent success. Usually a hopper dredge is used for this purpose because it can agitate without alteration and it can operate throughout the tidal cycle by agitating on the ebb tide and resorting to conventional hopper dredge operation on the flood tide. Occasionally other types of suction dredges are utilized for agitation dredging.

Use of current curves similar to those shown on Figures 11 through 14 can increase the efficiency of agitation dredging and will indicate the limit of the distance from the mouth of the stream at which such dredging may be expected to be effective. When there is fresh water flow the ebb tide near the surface will be preponderant over the flood tide. Thus, any material raised from the bottom, introduced into the surface or near surface layers, and retained in those layers will eventually be discharged from the river. Of course, the material discharged from the dredge at the surface will begin a gradual settlement to the lower layers just as it did when originally settling to the bottom either as suspended sediment or in the form of flocs. The flocculated material will probably settle faster than it originally did because of consolidation either in the shoal or in its movements along the bottom. It would appear, then, that little good is done by agitation late on the ebb tide. The material can be carried only a short distance seaward on the remaining ebb, and will then be returned a long distance upstream on the flood tide. Unless the mouth of the river is close at hand, even though the material be assumed to remain in the near surface layers, it may take several tidal cycles for it to be discharged to the ocean. In the meantime, during the last part of the ebb and the first part of the flood, and at slack periods, deposition and settlement will proceed with little resistance from turbulence. Thus the dredged material may return to the lower layers of the stream where the flood tide exceeds the ebb. It will then be returned to the shoals or redredged. It appears preferable to dredge on the last part of the flood tide and the first part of the ebb tide.

Similarly by obtaining and studying current curves and settling rates of material to be dredged by agitation, the point farthest upstream in the harbor at which material dredged may be expected to be discharged from the mouth of the river can be approximated. Further analysis will show the point of diminishing returns.

The location where the near bottom ebb and flood current flows are equal would appear to be a good point for agitation dredging of the slurry that moves back and forth along the channel bottom with the ebb and flow of the tide unless this point is situated so close to the ocean that the ebb current discharges the sediment from the mouth of the river. Also, if this point is so far up the river that the dredged sediment returns to the bottom layers of the stream before the upper layers can carry it to the mouth of the river, the dredging will be of little avail. Even when such a point is ideally located, the dredging of the slurry in this manner rather than from the shoals themselves after it has consolidated may not be economical, for a portion of the sediment in the

bottom layers is picked up by the upper currents during the process of erosion of the "so-called" salt water wedge. Thus a part of the material handled by the dredge would otherwise be discharged to the ocean by natural means. However, dredging of this type should reduce shoaling both upstream and downstream. Whether or not it would be an economic venture can be told only by trial.

The foregoing discussion shows that there may be possibilities of improving agitation dredging operations and efficacy by securing required basic data and by the intensive study thereof. With the operations guided by these studies it may be found that the use of relatively low cost agitation dredging where conditions show it to be appropriate will be followed by a considerable reduction in harbor shoaling and a substantial savings in harbor maintenance costs.

REFERENCES

(1) "Report of Salt Water Barrier," by Walter R. Young, Bulletin No. 22, Division of Water Resources, Dept. of Public Works, State of California.

(2) "Composition of Irrigation Water," by W. P. Kelley, Esq., and Discussion by Carl S. Scofield, Transactions ASCE, 1941, Vol. 106.

(3) "Salinity, Mississippi River at and Below New Orleans, La.," Report of the New Orleans District, Corps of Engineers.

(4) U. S. Public Health Service, Public Health Reports, Vol 61, No. 11, March 15, 1946.

(5) "Salinity Survey of the Delaware River," Sanitary Water Board, Pennsylvania Department of Health.

(6) "Principles of Sedimentation," by W. H. Twenhoffel.

(7) "The Oceans," by Sverdrup, Johnson, and Fleming.

(8) "The Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena," Report No. 1, Committee on Tidal Hydraulics, Corps of Engineers, U. S. Army, February 1950.

(9) "Model Law for Motion of Salt Water Through Fresh," by Morrough P. O'Brien and John Cherno; Transactions ASCE, Vol. 99, 1934.

(10) G. H. Keulegan in "Hydraulic Engineering," edited by Hunter Rouse.

(11) Paper presented at the Federal Inter-Agency Sedimentation Conference, Denver, Colorado, May 6-8, 1947, by Gerard H. Matthes, Consulting Engineer.

(12) "Plans for Improvement of Navigation Conditions and Elimination of Shoaling in Savannah Harbor, Georgia, and Connecting Waterways," Technical Memorandum No. 2-268, U. S. Waterways Experiment Station, Vicksburg, Mississippi.

(13) "Diversions from Alluvial Streams," by C. P. Lindner, Proceedings, ASCE, Vol 78, Separate No. 112.

(14) "Manual of Tide Observations," Special Publication No. 196, Revised (1941) Edition, U. S. Department of Commerce, Coast and Geodetic Survey.

(15) "Sabine-Neches Waterway (Salt-Water Guard Lock), Tex.," Committee on Rivers and Harbors, House of Representatives, Document No. 12, 68th Congress, 2d Session.

(16) "Tidal Waterways" Engineering Manual for Civil Works, Corps of Engineers, U. S. Army.

(17) "Density Currents in the Panama Canal," by J. S. Meyers, I.C.S. Memo 298, May 26, 1948, The Panama Canal.
(18) "Panama Sea-Level Canal, Miscibility of Fresh and Salt Water," by P. S. O'Shaughnessy, I.C.S. Memo 17, April 30, 1946, The Panama Canal.
(19) "Plans for the Improvement of the St. Johns River, Jacksonville to the Ocean," Technical Memorandum No. 2-244, U. S. Waterways Experiment Station, Vicksburg, Mississippi.
(20) "Salt Water Intrusion, Calcasieu River, Louisiana, and Connecting Waterways," Technical Memorandum No. 2-310, U. S. Waterways Experiment Station, Vicksburg, Mississippi.
(21) Salinity Studies of the Delaware River by the Philadelphia District, Corps of Engineers, U. S. Army.
(22) "Salinity Investigation in Charleston, S. C., Harbor, "Manuscript by E. A. Schultz, Charleston District, Corps of Engineers, U. S. Army.
(23) "Effect of Salinity on Current Velocities," by Ralph F. Rhodes, Prepared for the Committee on Tidal Hydraulics, Corps of Engineers, U. S. Army.
(24) "The Hydraulics of a Tidal River as Illustrated by Savannah Harbor, Georgia," by Ralph F. Rhodes, Savannah District, Corps of Engineers, U. S. Army.
(25) "Alabama-Coosa Branch of the Mobile River System (Determination of Salinity Line in Mobile River and its Tributaries)," House Document No. 773, 80th Congress, 2d Session.

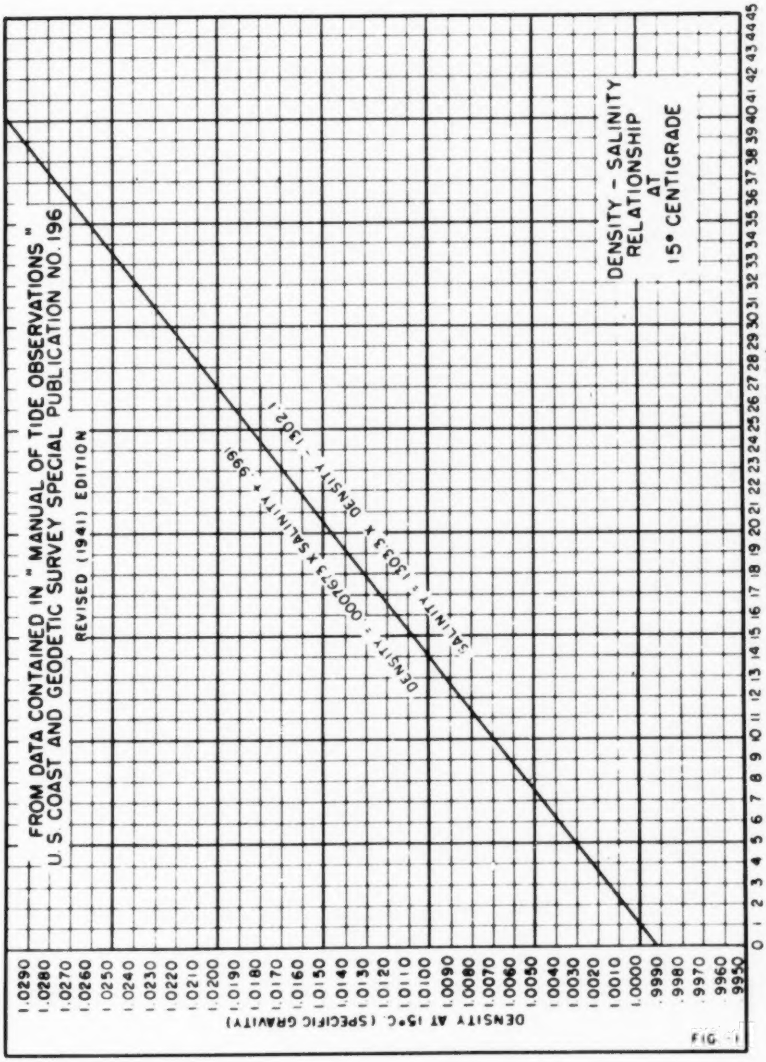

FROM DATA CONTAINED IN " MANUAL OF TIDE OBSERVATIONS "
U. S. COAST AND GEODETIC SURVEY SPECIAL PUBLICATION NO. 196
REVISED (1941) EDITION
DENSITY - SALINITY RELATIONSHIP AT 15° CENTIGRADE
SALINITY = 1303.3 X DENSITY - 1302.1
DENSITY = .0007673 X SALINITY + .9991
DENSITY AT 15°C. (SPECIFIC GRAVITY)
SALINITY IN PARTS PEP 1000 (TOTAL SALTS)

FIG. 1

DENSITY - TEMPERATURE RELATION
SALINE WATER

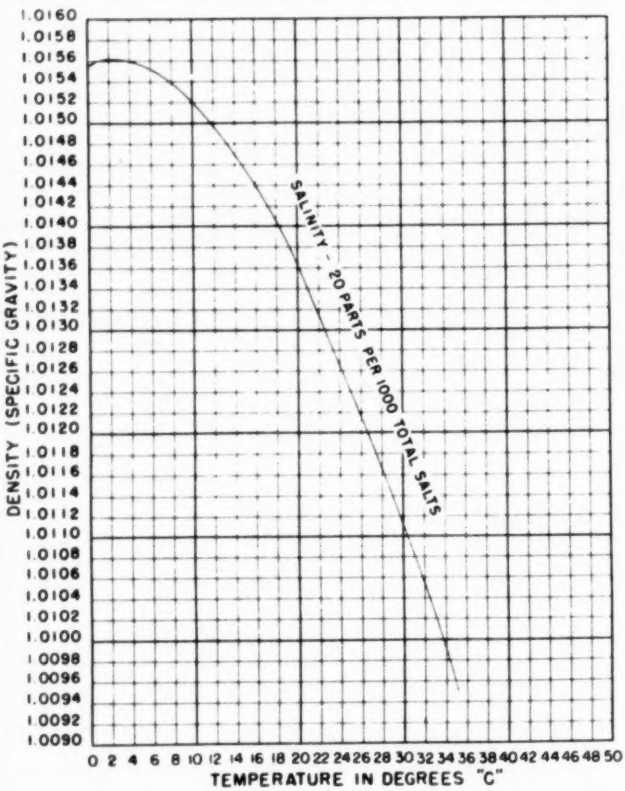
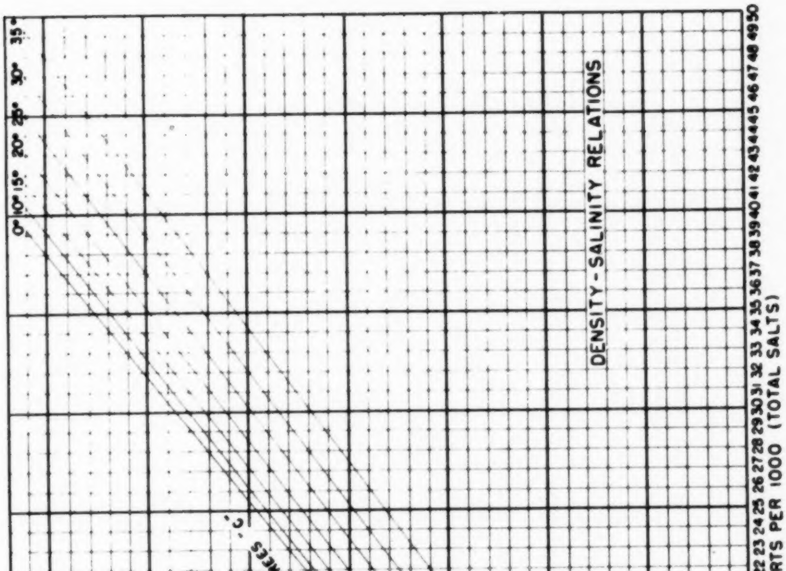
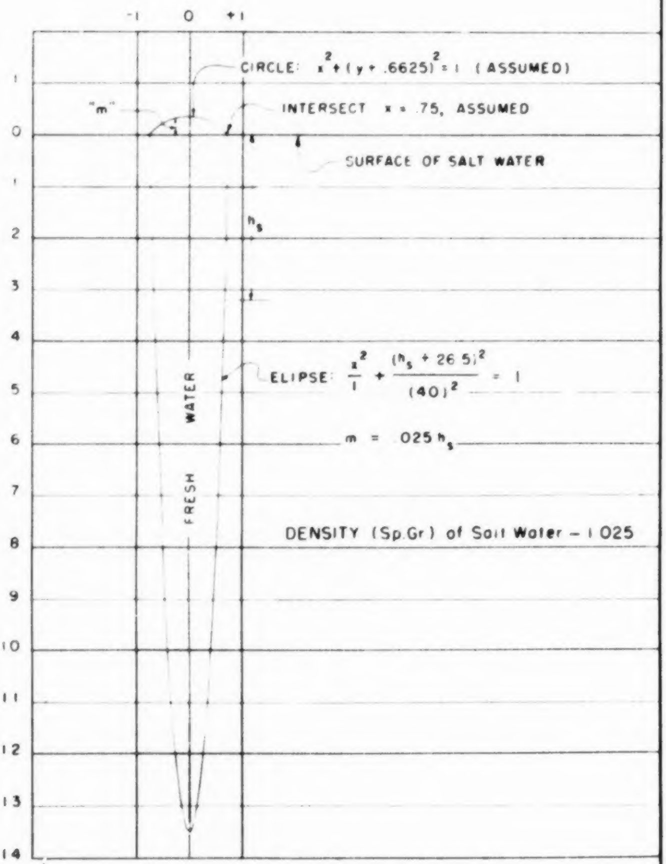


FIG. 2


DENSITY - SALINITY RELATIONS
SALINITY IN PARTS PER 1000 (TOTAL SALTS)
DENSITY (SPECIFIC GRAVITY)
TEMPERATURE IN DEGREES C.
0° 10° 15° 20° 25° 30° 35°
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50
1.0310 1.0300 1.0290 1.0280 1.0270 1.0260 1.0250 1.0240 1.0230 1.0220 1.0210 1.0200 1.0190 1.0180 1.0170 1.0160 1.0150 1.0140 1.0130 1.0120 1.0110 1.0100 1.0090 1.0080 1.0070 1.0060 1.0050 1.0040 1.0030 1.0020 1.0010 1.0000 .9990 .9980 .9970 .9960 .9950
FIG.-3



THE FRESH WATER BUBBLE

FIG -5

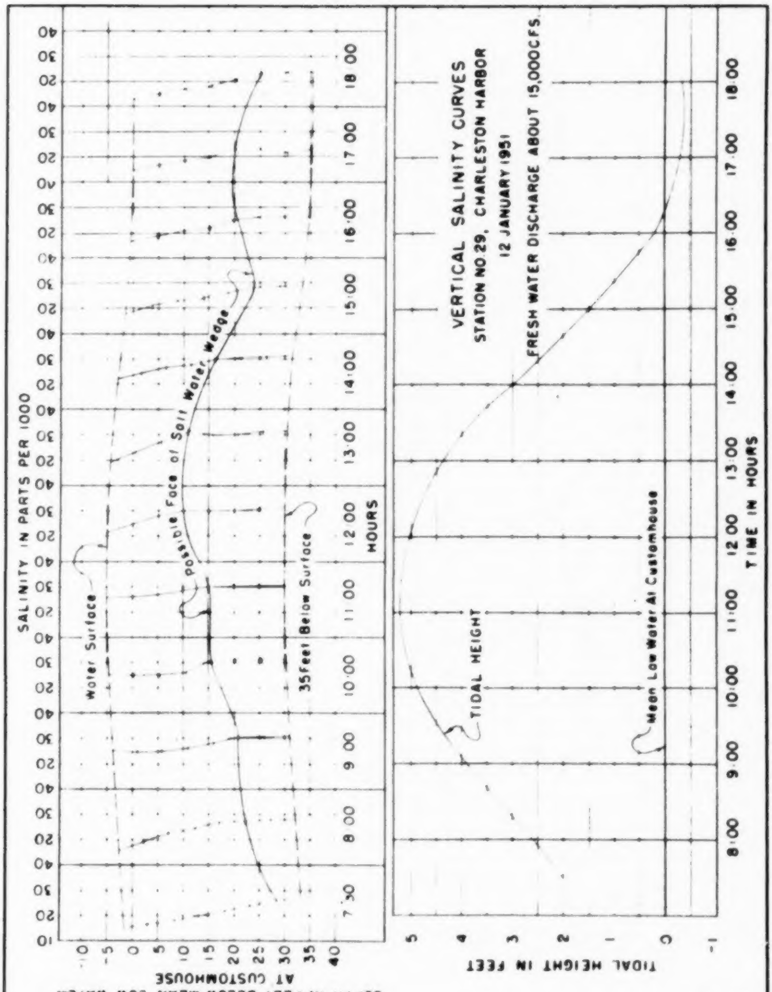
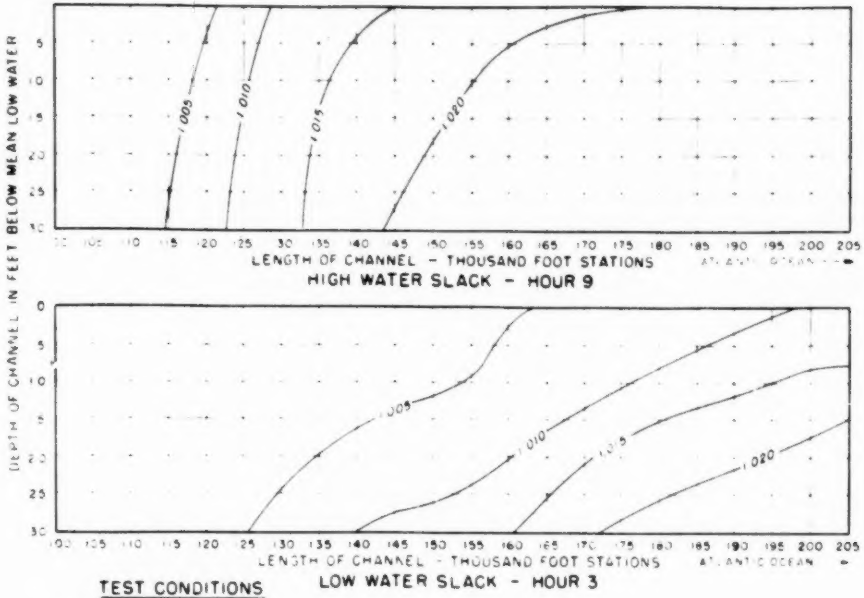

VERTICAL SALINITY CURVES
STATION NO 29, CHARLESTON HARBOR
12 JANUARY 1951
FRESH WATER DISCHARGE ABOUT 15,000 CFS.
SALINITY IN PARTS PER 1000
DEPTH IN FEET BELOW MEAN LOW WATER AT CUSTOMHOUSE
Water Surface
Possible Face of Salt Water Wedge
35 Feet Below Surface
HOURS
TIDAL HEIGHT
Mean Low Water At Customhouse
TIDAL HEIGHT IN FEET
TIME IN HOURS

FIG - 6

SALINITY PROFILES
FROM MODEL STUDY OF SAVANNAH HARBOR
30-FOOT CHANNEL



TEST CONDITIONS

MEAN TIDE REPRODUCTION
FRESH WATER DISCHARGE 4000 CFS
OCEAN DENSITY 1.024

FIG 7

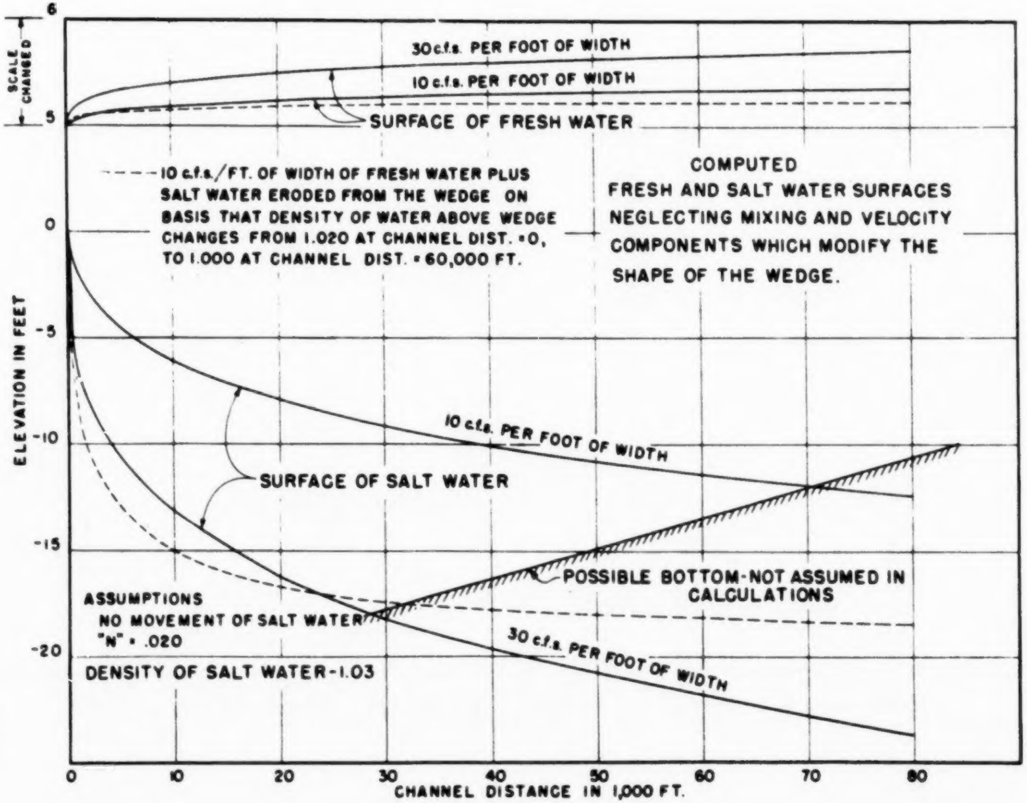
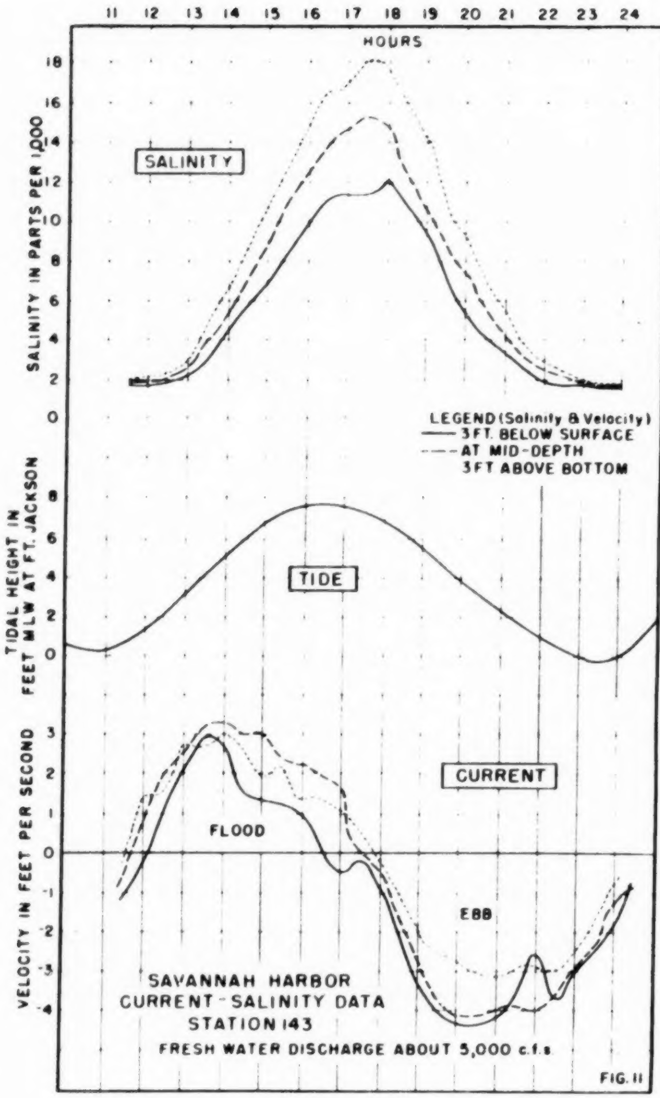
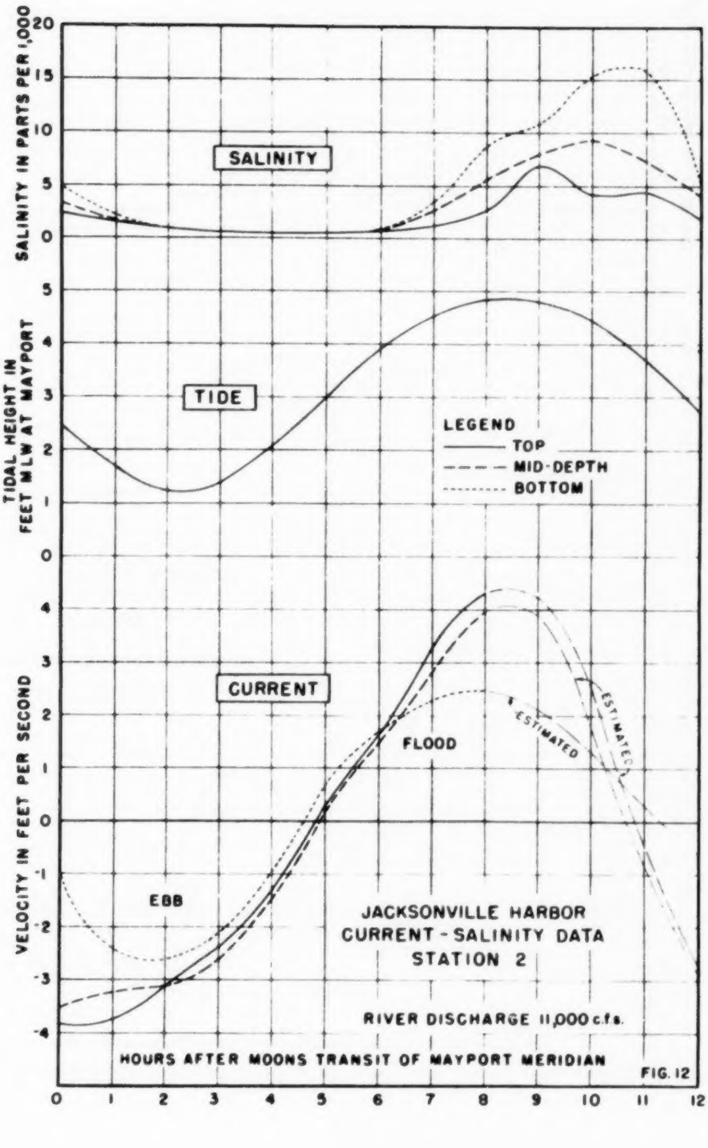

30 c.f.s. PER FOOT OF WIDTH
10 c.f.s. PER FOOT OF WIDTH
SURFACE OF FRESH WATER
SCALE CHANGED
10 c.f.s./FT. OF WIDTH OF FRESH WATER PLUS SALT WATER ERODED FROM THE WEDGE ON BASIS THAT DENSITY OF WATER ABOVE WEDGE CHANGES FROM 1.020 AT CHANNEL DIST. = 0, TO 1.000 AT CHANNEL DIST. = 60,000 FT.
COMPUTED
FRESH AND SALT WATER SURFACES NEGLECTING MIXING AND VELOCITY COMPONENTS WHICH MODIFY THE SHAPE OF THE WEDGE.
10 c.f.s. PER FOOT OF WIDTH
SURFACE OF SALT WATER
POSSIBLE BOTTOM-NOT ASSUMED IN CALCULATIONS
ASSUMPTIONS
NO MOVEMENT OF SALT WATER
"N" = .020
DENSITY OF SALT WATER-1.03
30 c.f.s. PER FOOT OF WIDTH
ELEVATION IN FEET
6
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
CHANNEL DISTANCE IN 1,000 FT.

FIG.10


HOURS
SALINITY
SALINITY IN PARTS PER 1,000
LEGEND (Salinity & Velocity)
3 FT. BELOW SURFACE
AT MID-DEPTH
3 FT ABOVE BOTTOM
TIDE
TIDAL HEIGHT IN FEET MLW AT FT. JACKSON
CURRENT
VELOCITY IN FEET PER SECOND
FLOOD
EBB
SAVANNAH HARBOR
CURRENT - SALINITY DATA
STATION 143
FRESH WATER DISCHARGE ABOUT 5,000 c.f.s.
FIG. 11


SALINITY IN PARTS PER 1,000
TIDAL HEIGHT IN FEET MLW AT MAYPORT
VELOCITY IN FEET PER SECOND
SALINITY
TIDE
CURRENT
LEGEND
TOP
MID-DEPTH
BOTTOM
FLOOD
EBB
ESTIMATED
ESTIMATED
JACKSONVILLE HARBOR
CURRENT - SALINITY DATA
STATION 2
RIVER DISCHARGE 11,000 c.f.s.
HOURS AFTER MOONS TRANSIT OF MAYPORT MERIDIAN
FIG. 12
0
1
2
3
4
5
6
7
8
9
10
11
12
20
15
10
5
0
5
4
3
2
1
0
4
3
2
1
0
-1
-2
-3
-4

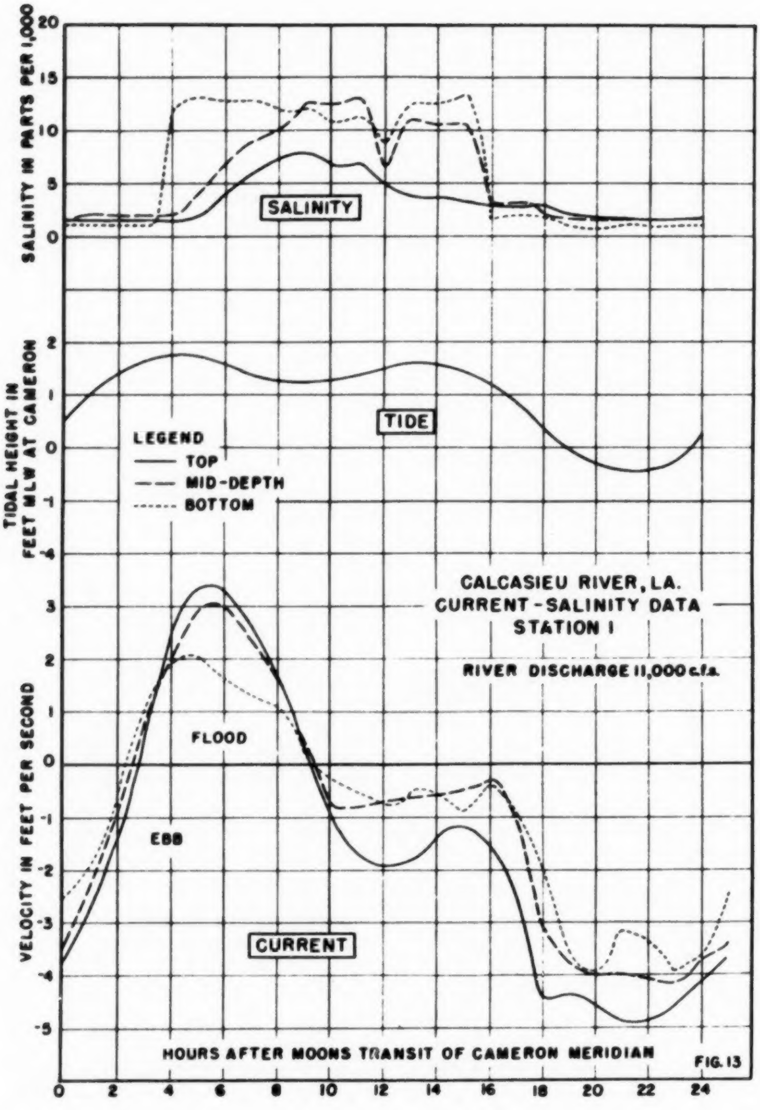

SALINITY IN PARTS PER 1,000
SALINITY
TIDAL HEIGHT IN FEET MLW AT CAMERON
TIDE
LEGEND
TOP
MID-DEPTH
BOTTOM
CALCASIEU RIVER, LA.
CURRENT-SALINITY DATA
STATION I
RIVER DISCHARGE 11,000 c.f.s.
VELOCITY IN FEET PER SECOND
FLOOD
EBB
CURRENT
HOURS AFTER MOONS TRANSIT OF CAMERON MERIDIAN

FIG. 13

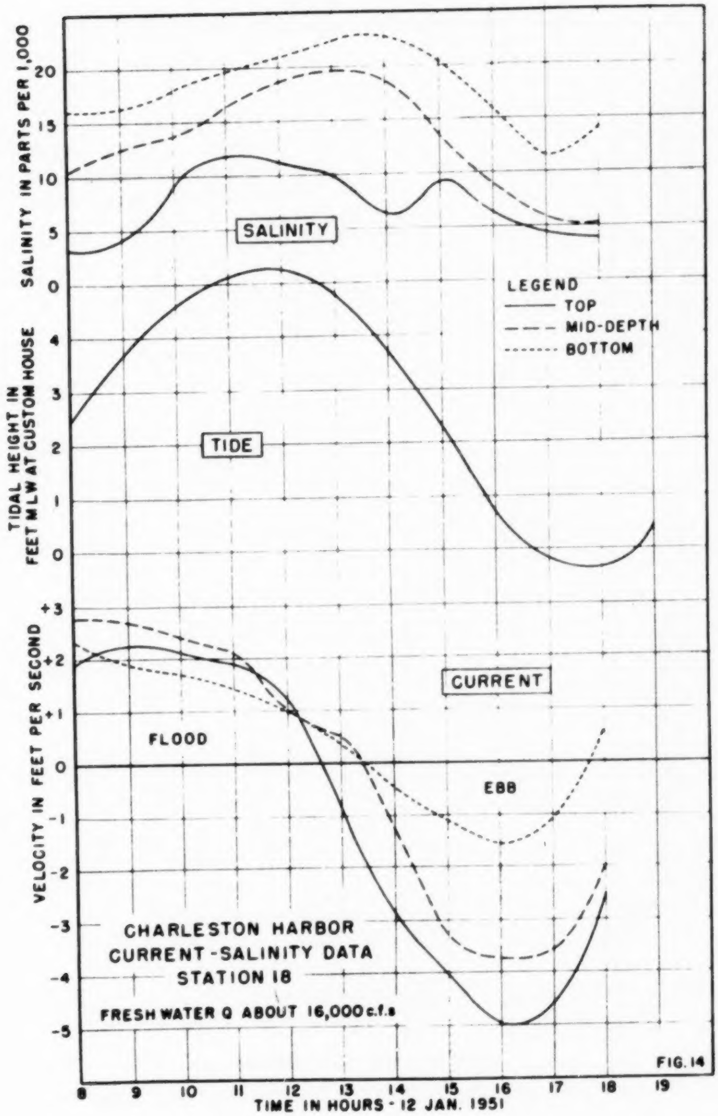

SALINITY IN PARTS PER 1,000
TIDAL HEIGHT IN FEET MLW AT CUSTOM HOUSE
VELOCITY IN FEET PER SECOND
SALINITY
TIDE
CURRENT
LEGEND
TOP
MID-DEPTH
BOTTOM
FLOOD
EBB
CHARLESTON HARBOR
CURRENT-SALINITY DATA
STATION 18
FRESH WATER Q ABOUT 16,000 c.f.s
TIME IN HOURS - 12 JAN. 1951

FIG. 14

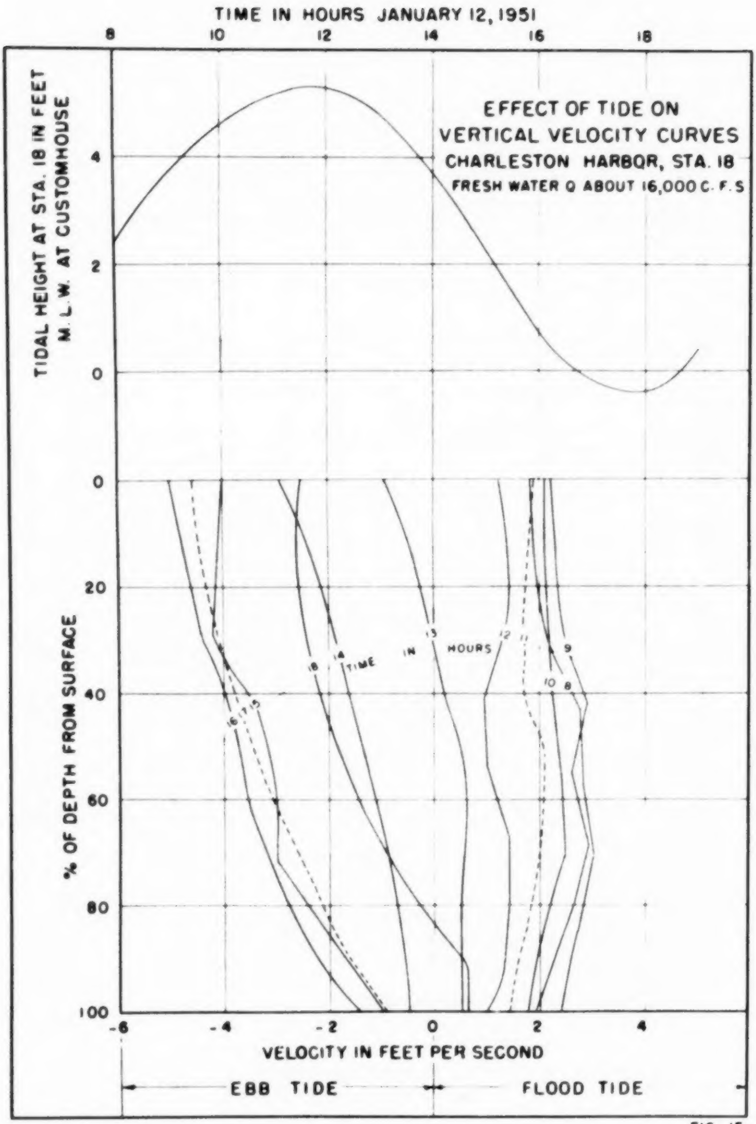
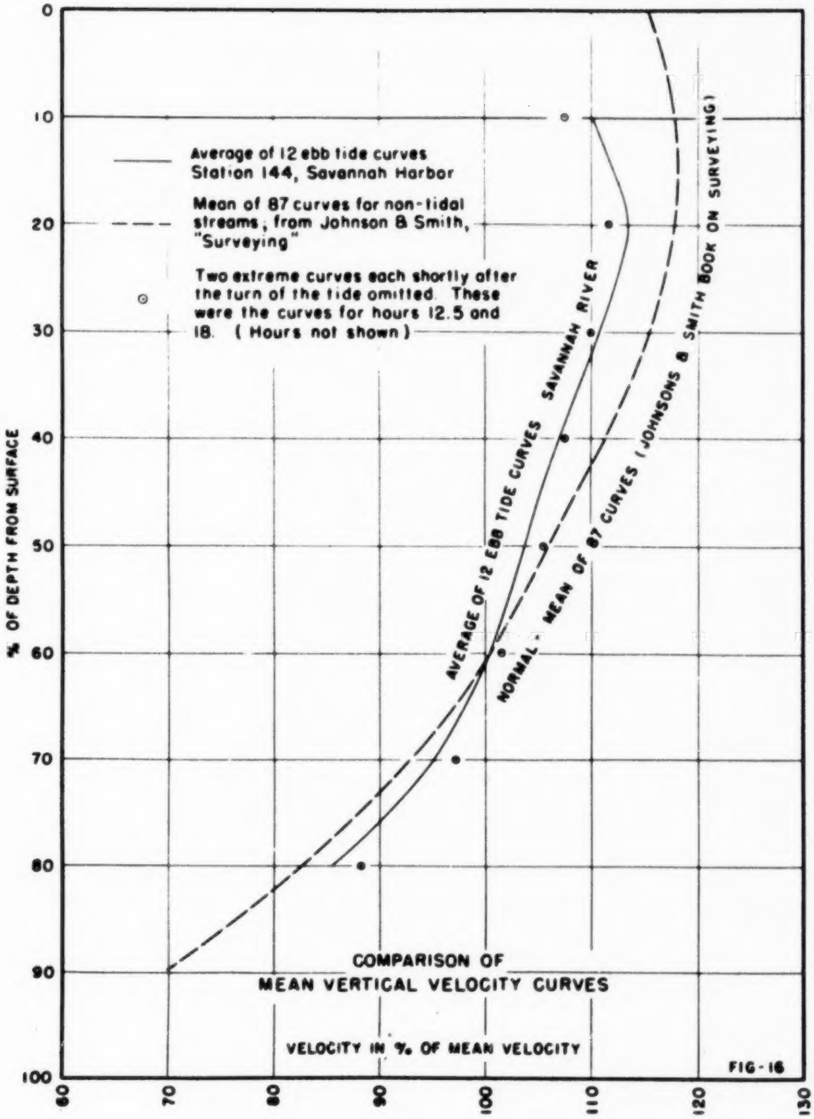

TIME IN HOURS JANUARY 12, 1951
8
10
12
14
16
18
EFFECT OF TIDE ON
VERTICAL VELOCITY CURVES
CHARLESTON HARBOR, STA. 18
FRESH WATER Q ABOUT 16,000 C. F. S
TIDAL HEIGHT AT STA. 18 IN FEET
M. L. W. AT CUSTOMHOUSE
4
2
0
0
20
40
60
80
100
% OF DEPTH FROM SURFACE
TIME IN HOURS
-6
-4
-2
0
2
4
VELOCITY IN FEET PER SECOND
EBB TIDE
FLOOD TIDE

FIG- 15



COMPARISON OF
MEAN VERTICAL VELOCITY CURVES